

Multilevel Vehicle Design: Fuel Economy, Mobility and Safety Considerations, Part B

Ground Vehicle Weight and Occupant Safety Under Blast Loading



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16th Annual ARC Conference

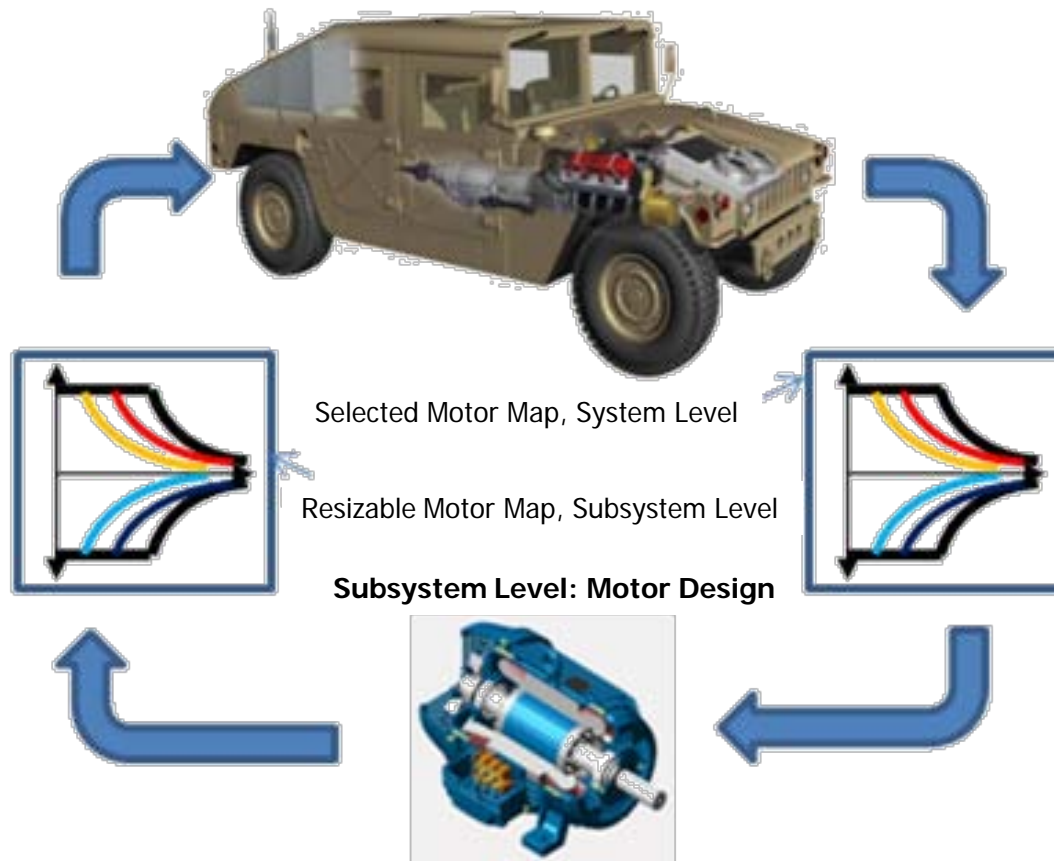
May 11, 2010

<http://editoriale.files.wordpress.com/2008/03/mrap.jpg>, accessed on April 22, 2010.

Report Documentation Page			Form Approved OMB No. 0704-0188		
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE 11 MAY 2010		2. REPORT TYPE N/A		3. DATES COVERED -	
4. TITLE AND SUBTITLE Multilevel Vehicle Design: Fuel Economy, Mobility and Safety Considerations, Part B Ground Vehicle Weight and Occupant Safety Under Blast Loading				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Steven Hoffenson, presenter (U of M); Panos Papalambros, PI (U of M); Michael Kokkolaras, PI (U of M); Sudhakar Arepally (TARDEC)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) US Army RDECOM-TARDEC 6501 E 11 Mile Rd Warren, MI 48397-5000, USA				8. PERFORMING ORGANIZATION REPORT NUMBER 20804RC	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) US Army RDECOM-TARDEC 6501 E 11 Mile Rd Warren, MI 48397-5000, USA				10. SPONSOR/MONITOR'S ACRONYM(S) TACOM/TARDEC	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S) 20804RC	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release, distribution unlimited					
13. SUPPLEMENTARY NOTES The original document contains color images.					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT SAR	18. NUMBER OF PAGES 31	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

Fuel Economy, Mobility and Safety

System Level: Battery, Gearbox, Occupant Compartment Design ; Motor Map Selection

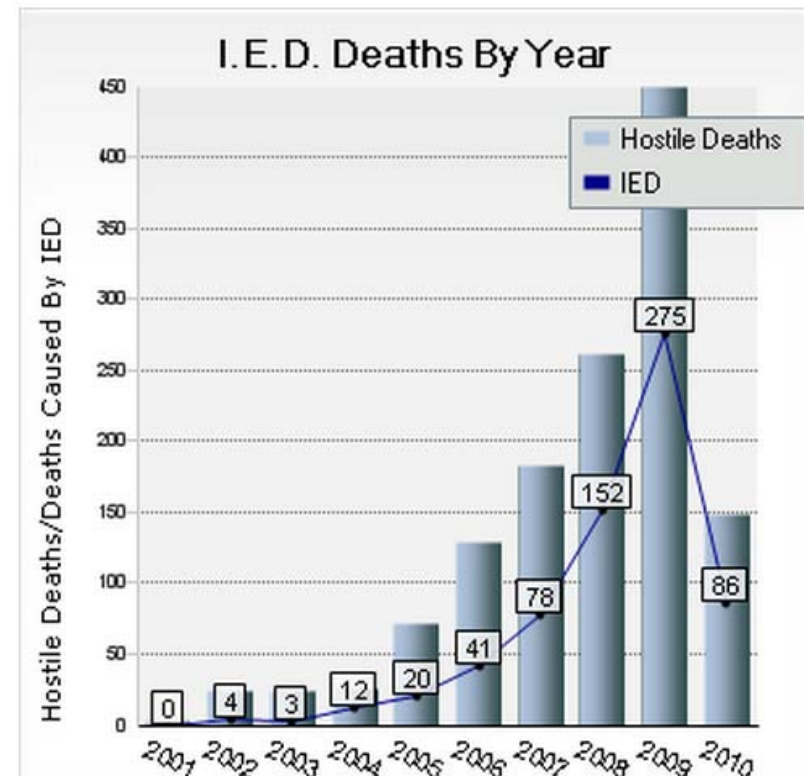


http://c0378172.cdn.cloudfiles.rackspacecloud.com/7770_9080764544.jpg, accessed on April 29, 2010.

<http://www.motor-design.com>, accessed on January 10, 2010.

Motivation

Underbody blast events are a top threat facing U.S. Army ground personnel



http://www.focusblog.ro/wp-content/uploads/2010/03/LAND_M1114_HMMWV_IEDed_lg.jpg, accessed April 29, 2010

iCasualties (2010). "IED Fatalities." <http://icasualties.org/oef>, accessed April 6, 2010.

Motivation

Vehicle weight has mixed effects on different design objectives



High Mobility Multipurpose Wheeled Vehicle (HMMWV)

2,700 kg

<http://www.amgeneral.com/vehicles/hmmwv/a2-series/details/m1097a2-base>
<http://www.globalsecurity.org/military/systems/ground/caiman-specs.htm>



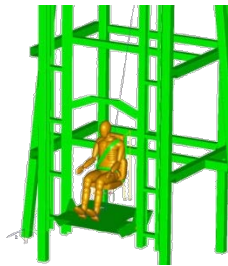
Mine Resistant Ambush Protected Vehicle (MRAP)

14,000 kg

Research Objective

Multi-objective optimization of ground vehicles for reduced weight and occupant injury

Determine occupant injury as a response to structural and occupant compartment design parameters



Develop surrogate models for vehicle and occupant responses to a blast event



Account for uncertainty in blast location and size

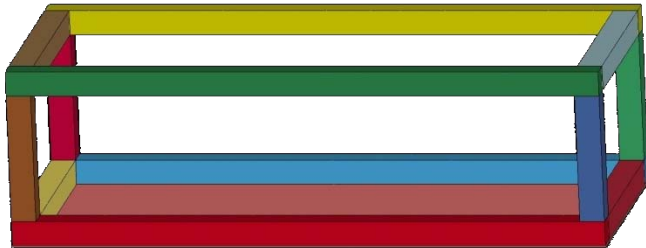
http://c0378172.cdn.cloudfiles.rackspacecloud.com/7770_9080764544.jpg, accessed on April 29, 2010.

http://mocoloco.com/art/archives/pickering_land_mine_mar_06.jpg, accessed on April 14, 2010.

Modeling Approach

Inputs:

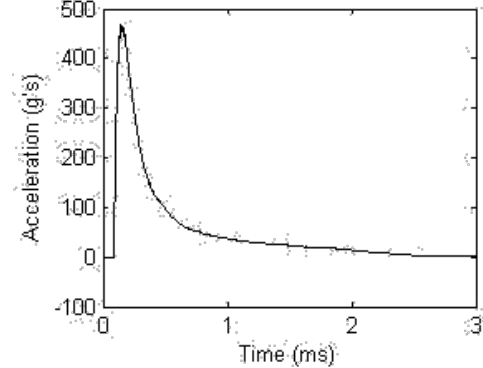
Vehicle Mass
Charge Location (x, y coordinates)
Charge Mass



Underbody Blast Simulation

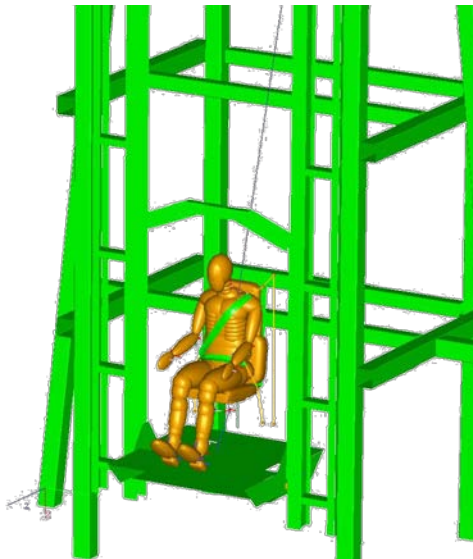


Blast Pulse of Vehicle



Inputs:

Blast Pulse (magnitude & duration)
Seat Cushion Stiffness
Seat Energy-Absorbing (EA)
System Stiffness



Drop Tower Simulation



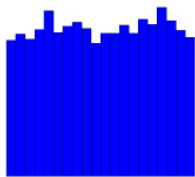
Outputs:

Upper Neck Axial Force
Lower Lumbar Axial Force
Lower Tibia Axial Force

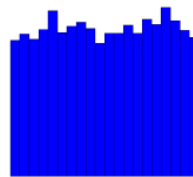
Charge Uncertainty



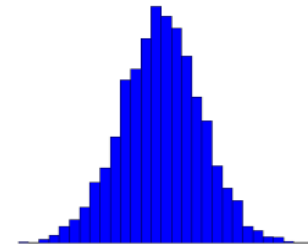
Field data about charge distribution is sensitive, so I postulate distributions:



Charge longitudinal/
x-location $\sim U(a,b)$
(m)

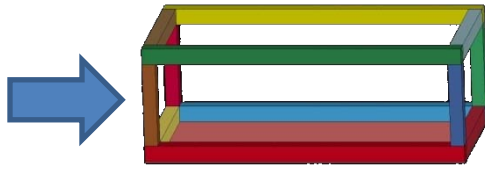
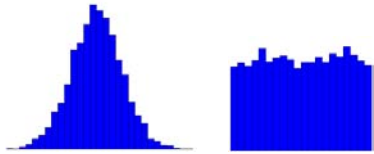


Charge lateral/
y-location $\sim U(a,b)$
(m)



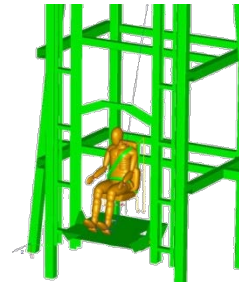
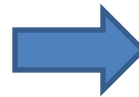
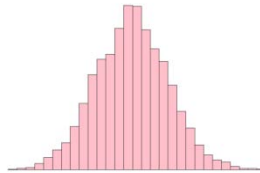
Charge mass $\sim N(\mu, \sigma)$
(TNT-equivalent)

**Uncertainty in
Charge Size &
Location**



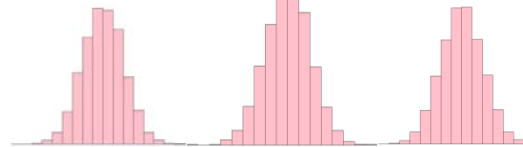
Underbody Blast Simulation

**Uncertainty in
Vehicle Peak
Acceleration**



Drop Tower Simulation

**Uncertainty in Occupant
Body Forces**



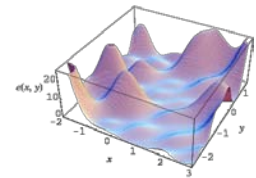
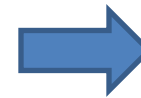
Upper Neck
Compression



Lumbar
Spine
Compression



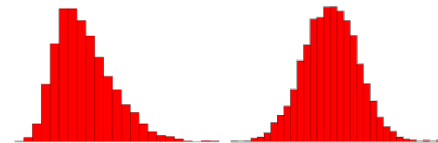
Lower Leg
Compression



Optimization to
Minimize Injury
Probability



**Uncertainty in
Optimal Seat System
Design Variables**



Charge Uncertainty Propagation

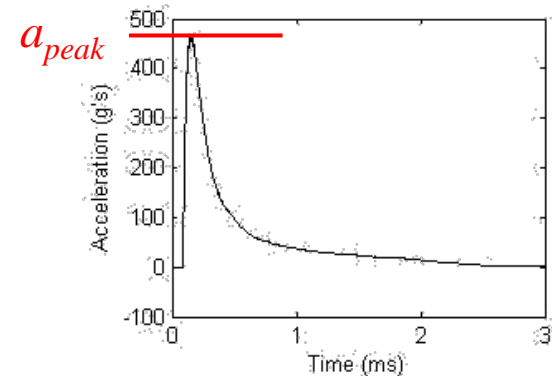
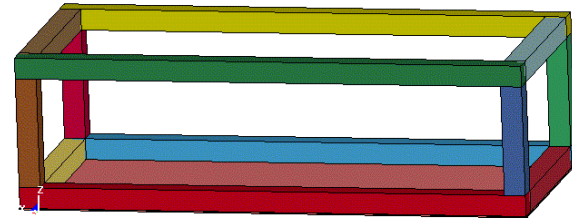
Structural Model

Input Variables:

Vehicle Mass (m_v)
Charge Location (x_c, y_c)
Charge Mass (m_c)

Output:

Blast pulse (a_{peak})

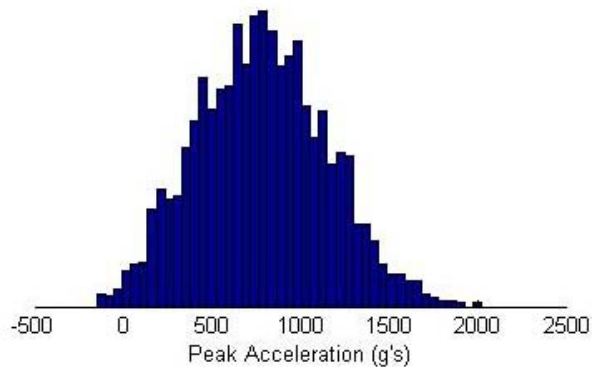


Surrogate model from linear regression on 100 data points:

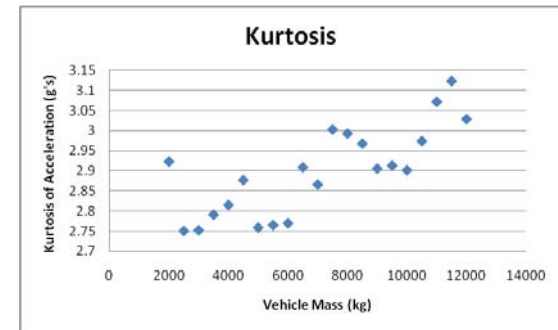
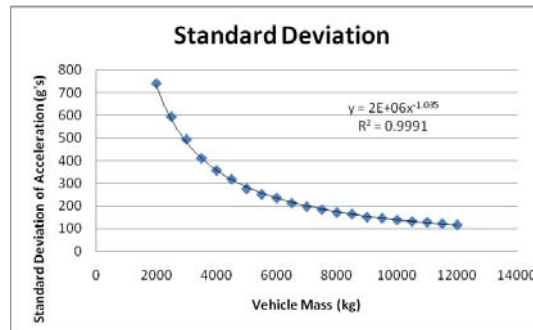
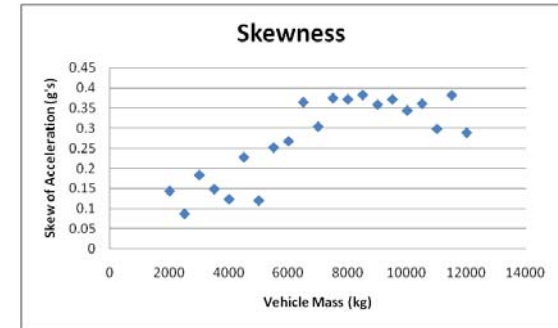
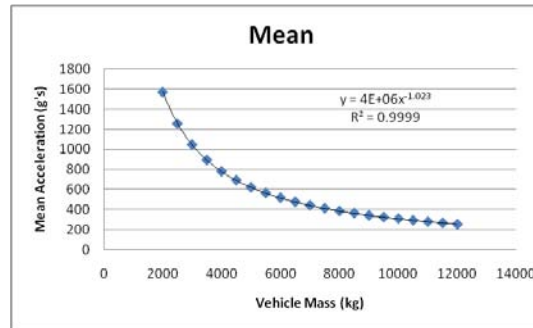
$$a_{peak} = \beta_0 + \beta_1 \frac{1}{m_v} + \beta_2 x_c + \beta_3 y_c + \beta_4 m_c + \beta_5 \frac{x_c}{m_v} + \beta_6 \frac{y_c}{m_v} + \beta_7 \frac{m_c}{m_v} + \beta_8 y_c m_c + \beta_9 y_c^2$$

Livermore Software Technology Corporation (2007). LS-DYNA Keyword User's Manual. http://lsc.com/pdf/ls-dyna_971_manual_k.pdf, accessed April 29, 2010.

Blast Pulse Uncertainty



Peak accelerations for
4,000 kg vehicle



Distribution moments plotted versus vehicle mass

$$\mu_{a_{peak}} = 4 \times 10^6 m_v^{-1.023}$$

$$\sigma_{a_{peak}} = 2 \times 10^6 m_v^{-1.035}$$

Occupant Model

Inputs:

Blast Pulse (a_{peak})

Seat Cushion Foam Stiffness (s_c)

Seat EA System Stiffness (s_{EA})

Outputs:

Upper Neck Axial Force (F_{neck})

Lower Lumbar Axial Force (F_{lumbar})

Lower Tibia Axial Force (F_{tibia})



Arepally, S. et. al. (2008). Application of Mathematical Modeling in Potentially Survivable Blast Threats in Military Vehicles.
<http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA496843&Location=U2&doc=GetTRDoc.pdf>, accessed on April 29, 2010.

Occupant Model

Surrogate model from linear regression on 500 data points:

$$F_{neck} = e^{(3.809 - 0.03954s_{EA} + 0.4289s_c + 0.003446a_{peak} + 0.0002161s_{EA}a_{peak} - 0.000001781a_{peak}^2)}$$

$$F_{spine} = 383 - 462s_{EA} + 416s_c + 1.4a_{peak} + 262s_{EA}s_c + 0.7s_{EA}a_{peak} + s_c a_{peak} - 232s_c^2 - 0.0006a_{peak}^2$$

$$F_{combined\ tibia} = 97 + 63s_{EA} - 495s_c + 3.7a_{peak} - 0.16s_{EA}a_{peak} - 0.38s_c a_{peak} + 99s_c^2 + 0.0003a_{peak}^2$$

U.S. Army aims for no more than
10% probability of moderate injury
(AIS2+)

Thresholds:



$$F_{neck} = 4 \text{ kN}$$



$$F_{lumbar} = 6.7 \text{ kN}$$



$$F_{tibia} = 5.4 \text{ kN}$$

Research and Technology Organisation (2007). "Test Methodology for Protection of Vehicle Occupants against Anti-Vehicular Landmine Effects." North Atlantic Treaty Organisation, Neuilly-sur-Seine Cedex, France. Accession number RTO-TR-HFM-090.

Optimization Formulation

General Safety Objective: minimize occupant injury

What is the explicit objective function?

$\min f(x)$ = probability of AIS2 Injury

Complication: unknown injury probability distributions

Thresholds:



$$F_{\text{neck}} = 4 \text{ kN}$$



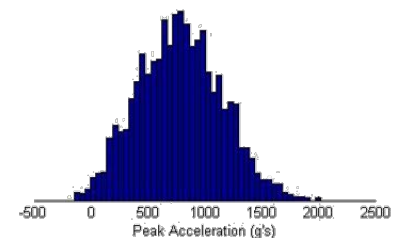
$$F_{\text{lumbar}} = 6.7 \text{ kN}$$



$$F_{\text{tibia}} = 5.4 \text{ kN}$$

$\min f(x)$ = body forces experienced when vehicle is attacked

Complications: uncertainty in charge parameters,
multiple body forces of interest



Formulation 1: Model

Objective: minimize the maximum of the body forces (percentage of threshold)

$$\min_{s_{EA}, s_c} \max \left(\frac{F_{neck}}{4kN}, \frac{F_{lumbar}}{6.7kN}, \frac{F_{tibia(combined)}}{5.4kN} \right)$$

where $a_{peak} = \mu_{a_{peak}}(m_v) = 4 \times 10^6 m_v^{-1.023}$

$$F_{neck} = F_{neck}(s_{EA}, s_c, a_{peak})$$

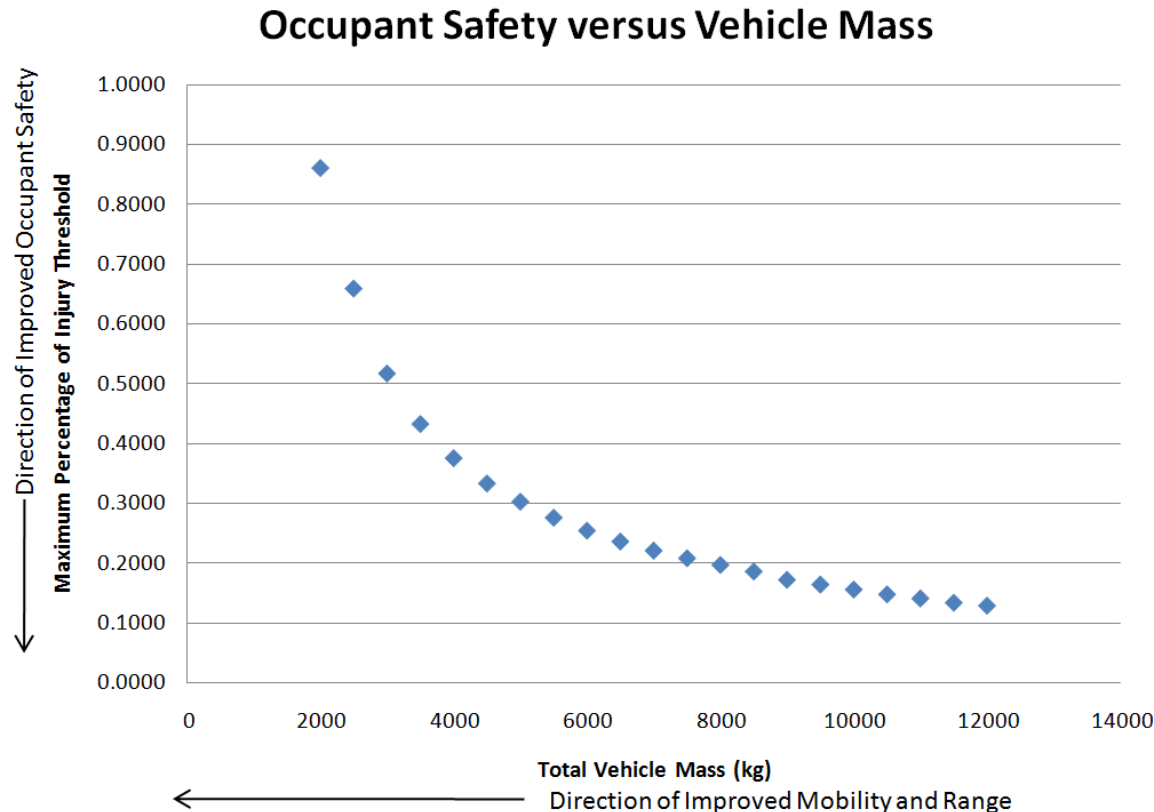
$$F_{lumbar} = F_{lumbar}(s_{EA}, s_c, a_{peak})$$

$$F_{combined\ tibia} = F_{combined\ tibia}(s_{EA}, s_c, a_{peak})$$

subject to $lb \leq s_{EA}, s_c \leq ub$

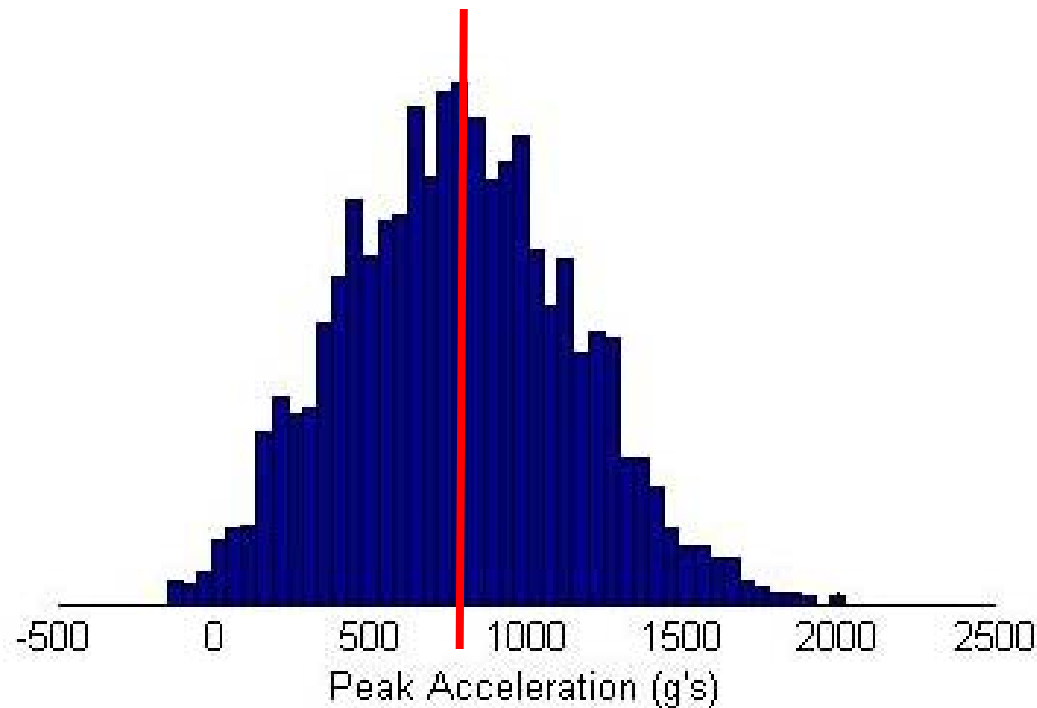
Formulation 1: Results

Objective: minimize the maximum of the body forces (percentage of threshold)



Formulation 1 Limitation

Minimizes body forces for a given vehicle mass for 50th percentile of charges



Formulation 2: Model

Objective: minimize the probability of “failure” to meet injury threshold

$$\min_{s_{EA}, s_c} \quad P_f = 1 - \Phi(a_{peak})$$

$$\text{where} \quad \Phi(a_{peak}) = \frac{1}{2} \left[1 + \operatorname{erf} \left(\frac{a_{peak} - \mu_{a_{peak}}}{\sqrt{2\sigma_{a_{peak}}^2}} \right) \right]$$

$$\mu_{a_{peak}}(m_v) = 4 \times 10^6 m_v^{-1.023}$$

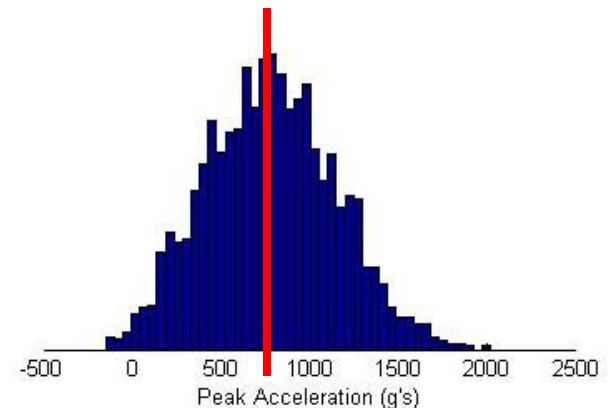
$$\sigma_{a_{peak}}(m_v) = 2 \times 10^6 m_v^{-1.035}$$

$$\text{subject to} \quad F_{neck} = g_1(s_{EA}, s_c, a_{peak}) \leq 4000$$

$$F_{lumbar} = g_2(s_{EA}, s_c, a_{peak}) \leq 6700$$

$$F_{combined\ tibia} = g_3(s_{EA}, s_c, a_{peak}) \leq 5400$$

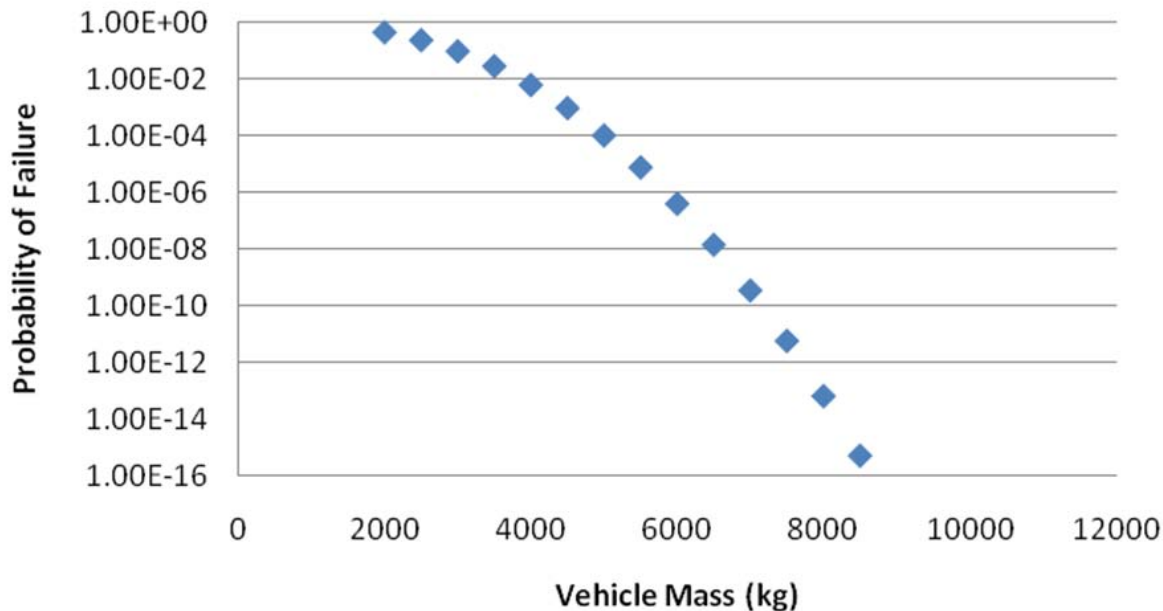
$$lb \leq s_{EA}, s_c \leq ub$$



Formulation 2: Results

Objective: minimize the probability of “failure” to meet injury threshold

Failure Probability vs. Vehicle Mass



Vehicle Mass (kg)	Probability of Failure
2000	4.60E-01
2500	2.45E-01
3000	9.93E-02
3500	2.97E-02
4000	6.43E-03
4500	9.90E-04
5000	1.07E-04
5500	8.06E-06
6000	4.20E-07
6500	1.51E-08
7000	3.69E-10
7500	6.16E-12
8000	6.99E-14
8500	5.55E-16
9000	0.00E+00

$$s_{EA} = 1.5, s_c = 2.0$$

Occupant Model with Floor Pad

Inputs:

Blast Pulse (a_{peak})

Seat Cushion Foam Stiffness (s_c)

Seat EA System Stiffness (s_{EA})

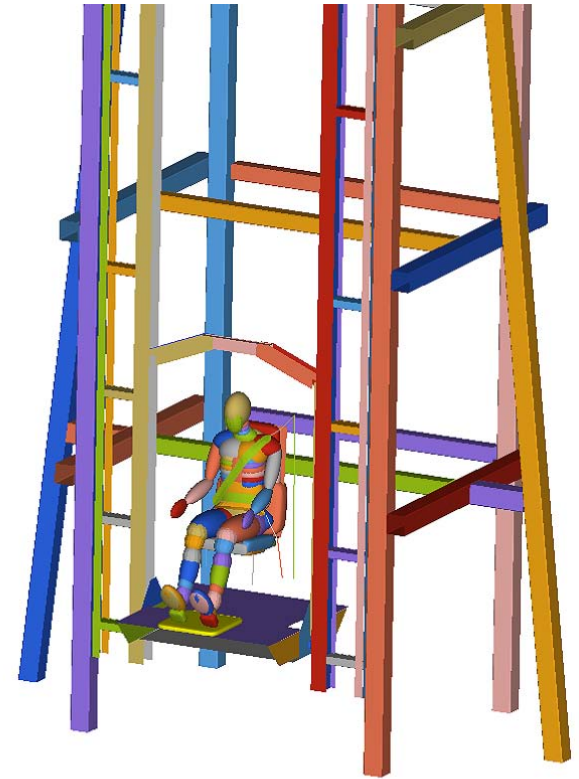
Floor Pad Foam Stiffness (s_f)

Surrogate model from linear regression on 300 data points:

$$F_{neck} = e^{\left(3.84 + 0.12s_{EA} + 0.88s_c + 0.002a_{peak} + 0.058s_{EA}s_c + 0.000084s_{EA}a_{peak} - 0.000063s_c a_{peak} - 0.058s_{EA}^2 - 0.14s_c^2 - 0.00000054a_{peak}^2\right)}$$

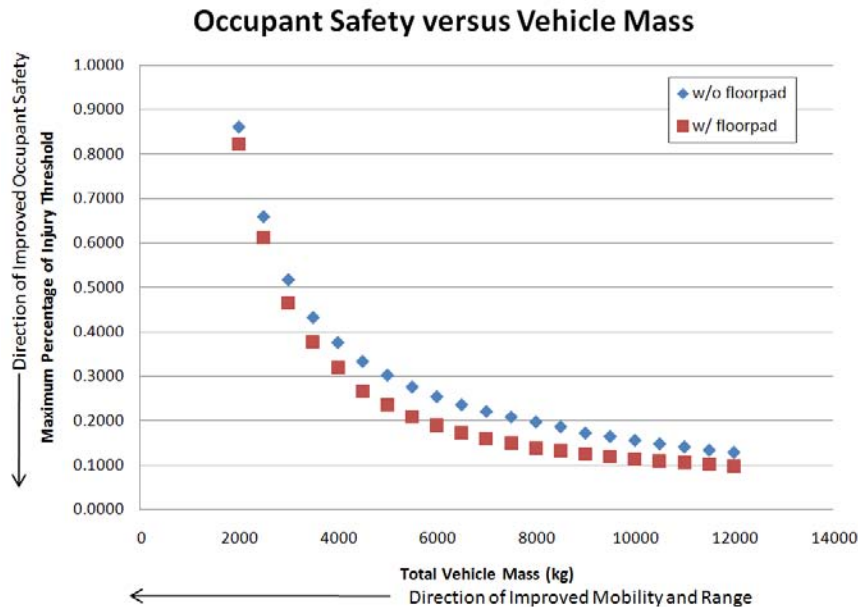
$$F_{spine} = e^{\left(5.664 + 0.12s_{EA} + 0.81s_c + 0.002a_{peak} + 0.062s_{EA}s_c + 0.000087s_{EA}a_{peak} - 0.000068s_c a_{peak} - 0.059s_{EA}^2 - 0.13s_c^2 - 0.00000056a_{peak}^2\right)}$$

$$F_{combined\ tibia} = 332 - 245s_c - 80.23s_f + 1.3a_{peak} + 35.84s_c s_f + 14.0s_f^2 + 0.0012a_{peak}^2$$

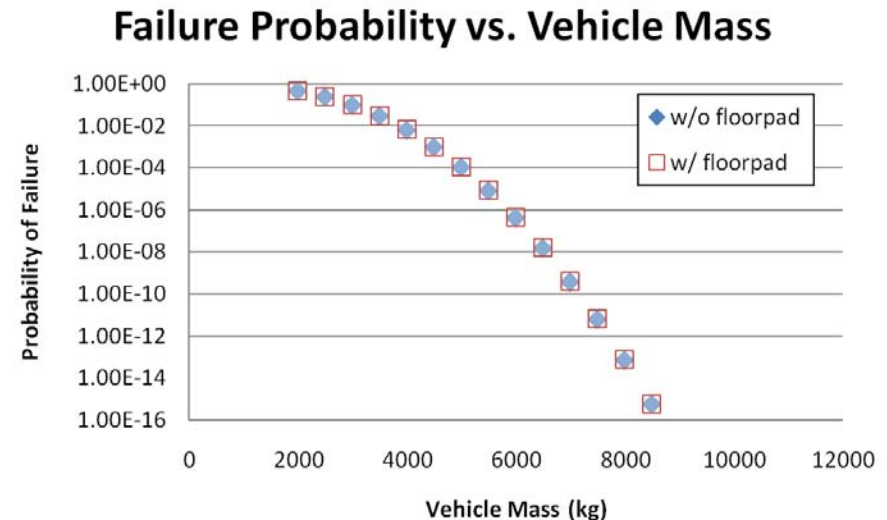


Results with Floor Pad

Objective 1: minimize the maximum of the body force percentages



Objective 2: minimize the probability of “failure” to meet injury threshold



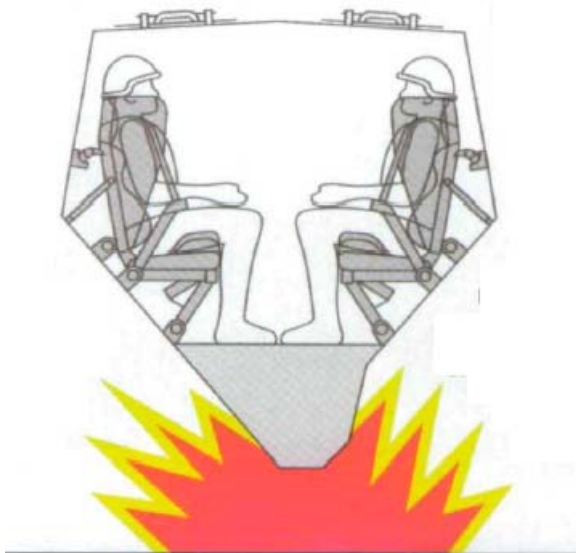
Summary

- Developed a modeling approach to evaluate structural and occupant responses to ground vehicle underbody blasts
- Fit surrogate models to reduce computational expense
- Demonstrated two optimization formulations and their results
 - Accounted for uncertainty in charge parameters
 - Quantified negative correlation between vehicle mass and occupant injury probability
- Added floor padding to reduce tibia impact

Ongoing Work



Structural energy absorption



Effects of v-shaped hull



Rollover safety modeling

http://www.defense-update.com/products/t/tarps_291009.html, accessed April 27, 2010.
http://www.usaasc.info/alt_online/images/080901_Photo2.jpg, accessed April 29, 2010.

Q & A





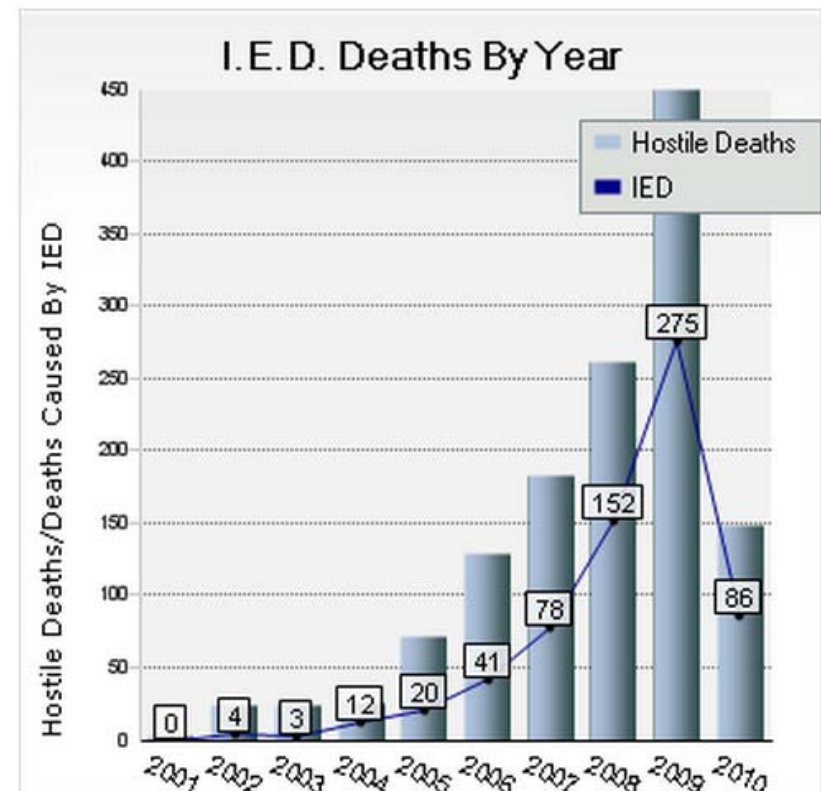
Backup Slides

Motivation

Underbody blast events are a top threat facing U.S. Army ground personnel

IED Fatalities

Period	IED	Total	Pct
2001	0	4	0.00
2002	4	25	16.00
2003	3	26	11.54
2004	12	27	44.44
2005	20	73	27.40
2006	41	130	31.54
2007	78	184	42.39
2008	152	263	57.79
2009	275	450	61.11
2010	86	150	57.33



Abbreviated Injury Scale

TABLE 1. Abbreviated Injury Scale (AIS)

AIS score	Injury
1	Minor
2	Moderate
3	Serious
4	Severe
5	Critical
6	Probably lethal*

* Although a perfect linear correlation with an AIS of 6 and mortality does not exist, survivability is unlikely.

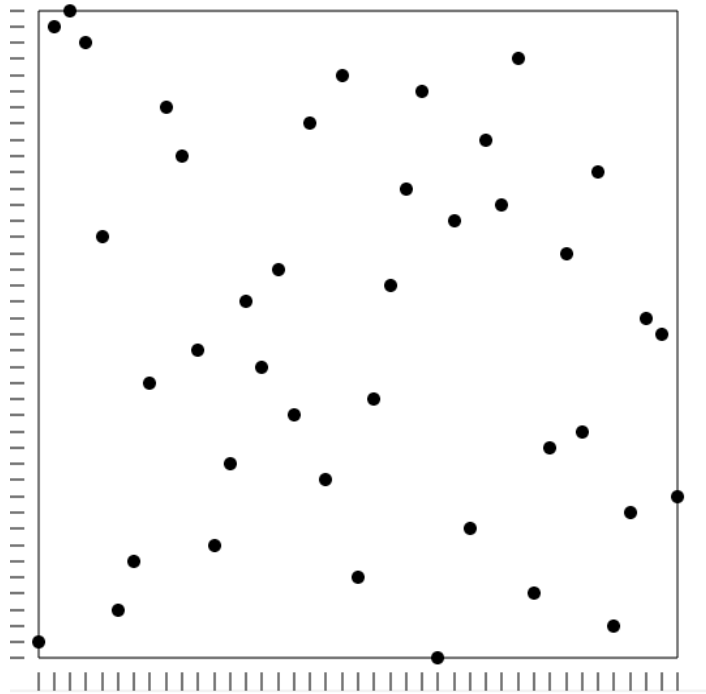
Examples of AIS 2

- Major skin laceration or avulsion with <20% blood loss
- Nerve contusions or lacerations
- Vertebral dislocation without fracture
- Herniated disc without nerve root damage
- Lower extremity bone fracture

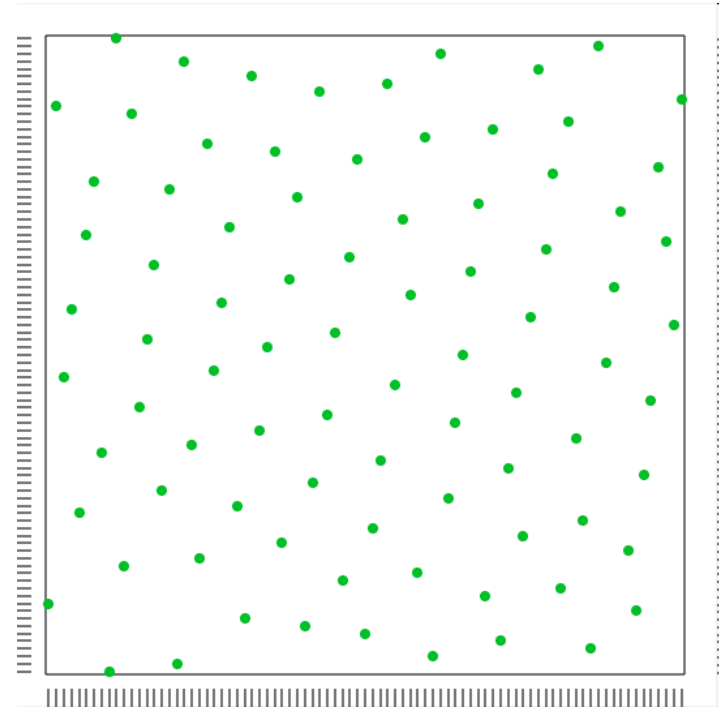
Center for Disease Control and Prevention, <http://www.cdc.gov/mmwr/preview/mmwrhtml/figures/r801a1t1.gif>, accessed on April 30, 2010.

Association for the Advancement of Automotive Medicine (1990), The Abbreviated Injury Scale, 1990 Revision. Des Plaines, IL.

Latin Hypercube Sampling



Latin Hypercube



Optimal Latin Hypercube

http://people.sc.fsu.edu/~burkardt/m_src/lcvt_dataset/lcvt_dataset.html, accessed on December 5, 2009.

Model Comparison

Without floorpad:

500 data points

$$F_{neck} = e^{(3.809 - 0.03954s_{EA} + 0.4289s_c + 0.003446a_{peak} + 0.0002161s_{EA}a_{peak} - 0.000001781a_{peak}^2)}$$

$$F_{spine} = 383 - 462s_{EA} + 416s_c + 1.4a_{peak} + 262s_{EA}s_c + 0.7s_{EA}a_{peak} + s_c a_{peak} - 232s_c^2 - 0.0006a_{peak}^2$$

$$F_{combined\ tibia} = 97 + 63s_{EA} - 495s_c + 3.7a_{peak} - 0.16s_{EA}a_{peak} - 0.38s_c a_{peak} + 99s_c^2 + 0.0003a_{peak}^2$$

R²

0.985

0.979

0.994

With floorpad:

300 data points

$$F_{neck} = e^{(3.84 + 0.12s_{EA} + 0.88s_c + 0.002a_{peak} + 0.058s_{EA}s_c + 0.000084s_{EA}a_{peak} - 0.000063s_c a_{peak} - 0.058s_{EA}^2 - 0.14s_c^2 - 0.00000054a_{peak}^2)}$$

$$F_{spine} = e^{(5.664 + 0.12s_{EA} + 0.81s_c + 0.002a_{peak} + 0.062s_{EA}s_c + 0.000087s_{EA}a_{peak} - 0.000068s_c a_{peak} - 0.059s_{EA}^2 - 0.13s_c^2 - 0.00000056a_{peak}^2)}$$

$$F_{combined\ tibia} = 332 - 245s_c - 80.23s_f + 1.3a_{peak} + 35.84s_c s_f + 14.0s_f^2 + 0.0012a_{peak}^2$$

R²

0.952

0.946

0.976

Formulation 1 Data

Without Floor Foam

Vehicle Mass (kg)	EA Stiffness	Cushion Stiffness	Maximum Injury Ratio
2000	1.5000	2.0000	0.8616
2500	1.1082	2.0000	0.6597
3000	0.6323	2.0000	0.5175
3500	0.2962	2.0000	0.4328
4000	0.2500	1.7909	0.3757
4500	0.2500	1.5907	0.3333
5000	0.2500	1.4406	0.3029
5500	0.2500	1.3039	0.2760
6000	0.2500	1.1905	0.2543
6500	0.2500	1.0942	0.2362
7000	0.2500	1.0110	0.2208
7500	0.2500	0.9415	0.2081
8000	0.2500	0.8789	0.1968
8500	0.2504	0.8183	0.1860
9000	1.5000	0.8094	0.1720
9500	1.5000	0.7929	0.1641
10000	1.5000	0.7754	0.1558
10500	1.5000	0.7582	0.1476
11000	1.5000	0.7437	0.1408
11500	1.5000	0.7284	0.1336
12000	1.5000	0.7178	0.1286

With Floor Foam

Vehicle Mass (kg)	EA Stiffness	Cushion Stiffness	Floorpad Stiffness	Maximum Injury Ratio
2000	0.2500	4.0000	0.1000	0.8219
2500	0.2500	2.2457	0.1000	0.6125
3000	0.2500	1.6494	0.7522	0.4655
3500	0.2500	1.4056	1.0632	0.3783
4000	0.2500	1.2530	1.2460	0.3203
4500	0.2500	1.1080	1.3507	0.2666
5000	0.2500	1.0172	1.4267	0.2351
5500	0.2500	0.9392	1.4854	0.2099
6000	0.2500	0.8702	1.5704	0.1892
6500	0.2500	0.8120	1.8208	0.1731
7000	0.2500	0.7603	1.8867	0.1598
7500	0.2500	0.7166	1.9425	0.1491
8000	0.2500	0.6736	1.9975	0.1393
8500	0.2500	0.6410	2.0391	0.1323
9000	0.2500	0.6042	2.0860	0.1247
9500	0.2500	0.5777	2.1199	0.1195
10000	0.2500	0.5449	2.1619	0.1134
10500	0.2500	0.5286	2.2053	0.1104
11000	0.2500	0.5036	2.2145	0.1060
11500	0.2500	0.4804	2.2441	0.1022
12000	0.2500	0.4588	2.2716	0.0986

Formulation 2 Data

Without Floor Foam

Vehicle Mass (kg)	EA Stiffness	Cushion Stiffness	Probability of Failure
2000	1.5	2.0	4.60E-01
2500	1.5	2.0	2.45E-01
3000	1.5	2.0	9.93E-02
3500	1.5	2.0	2.97E-02
4000	1.5	2.0	6.43E-03
4500	1.5	2.0	9.90E-04
5000	1.5	2.0	1.07E-04
5500	1.5	2.0	8.06E-06
6000	1.5	2.0	4.20E-07
6500	1.5	2.0	1.51E-08
7000	1.5	2.0	3.69E-10
7500	1.5	2.0	6.16E-12
8000	1.5	2.0	6.99E-14
8500	1.5	2.0	5.55E-16
9000	1.5	2.0	0.00E+00
9500	1.5	2.0	0.00E+00
10000	1.5	2.0	0.00E+00
10500	1.5	2.0	0.00E+00
11000	1.5	2.0	0.00E+00
11500	1.5	2.0	0.00E+00
12000	1.5	2.0	0.00E+00

$$a_{peak} = 1756.7 \text{ G's}$$

With Floor Foam

Vehicle Mass (kg)	EA Stiffness	Cushion Stiffness	Floorpad Stiffness	Probability of Failure
2000	1.65	4.0	0.10	4.61E-01
2500	1.65	4.0	0.10	2.46E-01
3000	1.65	4.0	0.10	1.00E-01
3500	1.65	4.0	0.10	3.01E-02
4000	1.65	4.0	0.10	6.54E-03
4500	1.65	4.0	0.10	1.01E-03
5000	1.65	4.0	0.10	1.10E-04
5500	1.65	4.0	0.10	8.36E-06
6000	1.65	4.0	0.10	4.40E-07
6500	1.65	4.0	0.10	1.59E-08
7000	1.65	4.0	0.10	3.94E-10
7500	1.65	4.0	0.10	6.66E-12
8000	1.65	4.0	0.10	7.65E-14
8500	1.65	4.0	0.10	5.55E-16
9000	1.65	4.0	0.10	0.00E+00
9500	1.65	4.0	0.10	0.00E+00
10000	1.65	4.0	0.10	0.00E+00
10500	1.65	4.0	0.10	0.00E+00
11000	1.65	4.0	0.10	0.00E+00
11500	1.65	4.0	0.10	0.00E+00
12000	1.65	4.0	0.10	0.00E+00

$$a_{peak} = 1754.5 \text{ G's}$$